30.

High Speed Photographs of Flying Fishes in Flight.

H. E. Edgerton
Massachusetts Institute of Technology
&
C. M. Breder, Jr.
New York Aquarium

(Plates I–VIII).

Introduction.

The study of the mechanism of flight of the Exocoetidae has long been handicapped by a lack of good photographs of the performance. Such knowledge as we have of the factors involved has been based on simple observation and the interpretation of studies on the morphology of the Exocoetidae. That this was still in a not altogether satisfactory state led Breder (1937 and 1938) to remark rather sharply about the general attitude on the problem. Further no one can deny that there are still a host of details, a knowledge of which would be both of practical aerodynamic and academic value.

The first satisfactory photographs of flying fishes in various stages of flight are presented herewith with such interpretations as may be made from them. The photographs were taken on the east coast of Catalina Island, California, at night, during July, 1940, by one of the authors, Edgerton. They all represent the species *Cypselurus californicus* (Cooper) and are all results of the high-speed electrical flash photography method developed at the Massachusetts Institute of Technology. The value of this device for biological pursuits concerning locomotor matters involving high speeds is obvious. See Edgerton & Killian (1939) for a comprehensive bibliography on technique. If it had been practicable, high-speed motion pictures would have been even more valuable and it is to be hoped that such may be made in the future. As it is the stills presented herewith show a host of items unsuspected and illuminate a variety of others which for long have resided in the limbo of half-knowledge. The time of exposure in all cases is about 1/10,000 of a second, which is sufficiently short to "stop" all motion.

Acknowledgment is made of the splendid cooperation of the Catalina Island Company which furnished the motor boat *Blanche W*. This ship is equipped with a 110 volt D. C. generator and search light for observing the flying fishes at night. A small converter was used to produce alternating current to operate the electrical flash equipment. Two flash lamps were used in parallel. One of these was an experimental lamp about four feet in length (in two sections) in a cylindrical reflector. The other was a spiral lamp in a spherical reflector that was loaned for the occasion by the Los Angeles *Herald-Express*.[1] The straight tube was mounted on a pipe-work frame as far out over the water as possible, while the other was hand-held and directed at the fish that was photographed. A miniature Speed Graphic camera was used. A photograph is shown of the entire arrangement on the foredeck of the *Blanche W* in Plate I, Fig. 1.

Analysis of Plates.

The details which these photographs show are analyzed in the following section while the resulting interpretations are given under the heading "Discussion," both the remarks and interpretations being those of Breder.

Plate II, Fig. 2. The fish in full flight. Since the right pectoral is evidently arched upward near its center of pressure it would appear that the fish is rolling to that side with the left pectoral high. At the same time the tail is being swung to the right as is evidenced by the weaker central rays bending to the left. This would then represent normal resistance to extrinsic turning with banking to the right. Since the effects are

[1] This second lamp is the same as the Eastman Kodatron Speedlamp.

both slight, as is evident, it should represent an incipient turn of large radius which is being corrected. It may be noted that the right pelvic also appears to be pressed upwards with the left normal. The dorsal fin so far as can be seen in this picture seems unaffected. This shows well the extent of expansion of the wing surfaces under actual flight. Dead and preserved material give the impression of much less wing area due to shrinkage of the delicate membrane between the supporting ribs.

Plate III, Fig. 3. Just before emergence the paired fins may be seen closely appressed to the sides, while the upper caudal lobe already raises a wake, throwing spray high in the air before the head of the fish breaks the surface.

Plate III, Fig. 4. Similar to Fig. 3 but with even greater spray throwing and the fish describing a curve. It is doubtful if this attempt actually lead to a flight.

Plate IV, Fig. 5. Two fish just at emergence. The pectorals are lifted but the pelvics seem to be only about half extended. At the extreme left are to be seen the first few flicks of spray raised by the upper caudal lobe. The emergence of the snout and body is represented by the heavy mass of spray. Note the extent of travel by the fish before the earliest spray has fallen.

Plate IV, Fig. 6. Full lateral view of a fish just before taking off. Both pectorals show a large amount of arching due to the pressure on them just before flying speed is obtained. The pelvics are only partly, if at all, unfolded. When this occurs the tail lifts and the greater amount of supporting surface relieves the load on the pectorals.

Plate V, Fig. 7. A diagonal view of a fish about to take off. The one visible pelvic appears to be about one-half expanded. Note the zigzag track which marks the "taxi" period and gives some idea of the value of each tail thrust in terms of the fish's length.

Plate VI, Fig. 8. A fish coming head on while in the "taxi" period. Apparently the pelvics are still being held close to the body for, if otherwise, in this photograph they should be conspicuous. As usual during this time the fish appears to be rolling badly, at the moment bearing down on the right pectoral and lifting the left. As some measure of the vigor of this rolling movement the flexible posterior margin of this fin is clearly bending down as the fin presses upward. It is this rolling that has given rise to the oft-repeated claim of wing flapping flight in these fishes.

Plate VII, Fig. 9. A fish just having cleared the water and steadying off to a smooth glide. The pelvics are still at a sharp angle pressing the tail upward. A moment later they would be approximately parallel to the pectorals.

Plate VII, Fig. 10. A second view of essentially the same position as that of Fig. 2 but not as marked a turning. The left pectoral of this fish has been damaged on its posterior border. Another specimen in the background is just leaving the water with the long lower caudal lobe still immersed.

Plate VIII, Fig. 11. A fish not quite maintaining flying speed. The body is somewhat arched in a vertical plane anticipatory to the tail's touching the surface of the water, when the "taxi" stage will be resumed and flight continued without complete submergence.

Discussion.

The photographic evidence here recorded is in good agreement with recent descriptive interpretation, *e. g.* Breder (1930), Hubbs (1933, 1935 and 1937), Carter & Mander (1935), Forbes (1936), and Loeb (1936). Reference to these papers shows that nearly all of the descriptive details given by them are evident from these photographs. In addition there are a number of items that could not be made out by field observation or interpretations based on anatomical study.

For example, in Figs. 6, 7 and 8 it may be seen that the mouth is held open. In all the others this feature cannot be distinguished because of position or some other reason. If this can be taken to mean that flying fishes usually or normally hold their mouths open during flight it is to say the least surprising. Even that they ever do was not expected. Two reasons for holding the mouth closed would be to preserve intact the streamline form of the head and to prevent the desiccating effect of a current of air passing over the delicate gill membranes. However this may be it is clear that these fishes do not always preserve form and conserve moisture by this simple expedient.

The two pictures of Plate III showing the fishes completely submerged and swimming nearly parallel with and very close to the surface indicate another unexpected feature; that of throwing spray with their tails before breaking the surface. All this happens so quickly that under mere ocular observation it is normally lost in the general flurry of the fish's plunging out into the air. Checking back, however, the proportions of these fish are such that the upper caudal lobe would project through the surface if they were swimming close to and parallel to it. Actual measurements show that the tail tip of a *Cypselurus californicus* 12 inches in standard length is a little over ¾ inch above the level of the flat back while the dorsal fin when erect is not quite ½ inch above the back. In other words a fish 12 inches long would be just breaking the surface film with its tail tip when swimming with ¾ inch of water over its back. This would seem to indicate that these fishes travel in this fashion just prior to emerging for some little distance, for otherwise it would be very unlikely that the photographer could get such photographs at all. Their sometimes apparent relatively steep angle of emergence is then probably generally due to the rapid tip up of the snout as the unfolding wings encounter air resistance. An angle of emergence of more than about 4° would prevent the tail and dorsal from breaking the surface before the snout came out. Incidentally these photographs show very good agreement with the sketches of Hubbs (1933).

In considering the various flexures of the fin rays that are shown in these photographs it must be borne in mind that these are long, thin, more or less flexible rods that are attached only at their bases and there operated by relatively small muscle bundles. Since the fish can only wave these rods about in various ways, mostly backward and forward and to a lesser degree up and down and since they have no voluntary control over the curvature of them it follows that the contortions shown are the result of wind pressure. This being the case the interpretation of the meaning of the curves seen becomes relatively simple. Even, as in these cases, where we have no direct knowledge of what the fish was doing before or after the instant of exposure, these curves, as indicated under "Analysis of Plates," give clues as to what the fish was undertaking.

In Fig. 11, for example, it is clear that the fish is descending and is all set for a renewal of the "taxi" period. Note that the wings are relatively straight and show a large lateral dihedral, for stability, while in Fig. 6, where the fish is driving ahead under the impulse of powerful tail thrusts, the wings held at a lower angle (see the basal part) are actually blown back and up and cupped by wind pressure. In other words they are loaded relatively more heavily than, as in Fig. 11, where the fish is merely falling freely.

Many other points already fairly well understood are reinforced by the details in these photographs. The next logical step looking toward a further clarification of exocoetid flight would be the application of high-speed cinematography whereby actual series of steps in this performance could be studied. Carter & Mander (1935) used motion picture technique to check the speed of flight but presumably they obtained a very small image not of value in studying details of manipulation of the fishes' structures.

Recently Woodcock (1940a and 1940b) has discussed the instability of air over the ocean showing that bands of updraughts occur, by an ingenious noting of the differential behavior of soaring gulls. These bands are responsible for the lines of Sargassum commonly found in the Atlantic according to the studies of Langmuir (1938). Since exocoetids may fly in a straight line or in various curving flights it may well be that these too are taking advantage of such atmospheric characteristics instead of merely being blown off their course as has been generally assumed. Carter & Mander (1935) indicated that they found their fish flying greater distances over rough water than over smooth and inferred that advantage was taken of the greater air turbulence in the former condition. Hubbs (1933 and 1936) could not find a difference in duration of flight to be correlated with travel over smooth or rough water. In any case the situation calls for a study of the flight of these fish in the light of the work of Woodcock on gulls and in reference to the general recent advances of micrometerology.

Bibliography.

Breder, C. M., Jr.

1930. On the structural Specialization of Flying Fishes from the Standpoint of Aerodynamics. *Copeia*, No. 4: 114–121.

1937. The Perennial Flying Fish Controversy. *Science* **86** (2236): 420–422.

1938. A Contribution to the Life Histories of Atlantic Ocean Flyingfishes. *Bull. Bingham Oceanographic Coll.* **6** (5): 1–126.

Carter, G. S. & Mander, J. A. H.

1935. The Flight of the Flying-Fish, Exocoetus. *Rep. Brit. Assn. Adv. Sci.*, **105**: 383–384.

Edgerton, H. E. & Killian, J. R.

1939. Flash. Hale, Cushman & Flint. Boston.

Forbes, A.

1936. Flying Fish. *Science*, N. S., **83**: 261–262.

Hubbs, C. L.

1933. Observations on the Flight of Fishes, with a Statistical Study of the Flight of the Cypselurinae and Remarks on the Evolution of the Flight of Fishes. *Pap. Mich. Acad. Sci., Arts and Letters*, **17**: 575–611.

1935. Nature's Own Seaplanes. *Smiths. Rep.*, **1933**: 333–348.

1937. Further Observations and Statistics on the Flight of Fishes. *Pap. Mich. Acad. Sci., Arts and Letters*, **22**: 641–660.

Langmuir, I.

1938. Surface Motion of Water Induced by Wind. *Science*, **87**: 119–123.

Loeb, L. B.

1936. The "Flight" of Flying Fish. *Science*, N. S., **83**: 260–261.

Woodcock, A. H.

1940a. Observations on Herring Gull Soaring. *Auk*. **57**: 219–224.

1940b. Convection and Soaring Over the Open Sea. *Jour. Mar. Res.* **3**: 248–253.

EXPLANATION OF THE PLATES.

Photographs by Dr. H. E. Edgerton. Taken at night by means of a Kodatron type of electrical flash lamp. Photographs all unretouched. All specimens are *Cypselurus californicus* (Cooper).

Plate I.

Fig. 1. The photographic equipment and its arrangement as used for taking pictures of flying fish in flight.

Plate II.

Fig. 2. A fish in full flight. The object in the upper left corner is part of the special illuminating device.

Plate III.

Fig. 3. Just before emergence, showing that the water is splashed before the fish breaks the surface.

Fig. 4. A more advanced stage in the water splashing period.

Plate IV.

Fig. 5. Two fish just about to leave the water near the end of the "taxi" stage.

Fig. 6. Full lateral view of a fish in the "taxi" stage.

Plate V.

Fig. 7. A diagonal view of an advanced "taxi." Note the trail left by the oscillating tail.

Plate VI.

Fig. 8. Head on view of a fish in an advanced "taxi." Note the evidences of roll in the differentially warped wings.

Plate VII.

Fig. 9. Just as the tail raises after the "taxi" stage.

Fig. 10. One fish in full flight in the foreground. Note the torn left wing. Another in the background with only the long lower caudal lobe immersed.

Plate VIII.

Fig. 11. Losing flying speed and about to dip the tail in the water for a resumed "taxi."